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Wu et al.

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(54) **IMAGE SENSOR WITH COLOR PIXELS HAVING UNIFORM LIGHT ABSORPTION DEPTHS**

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(21) Appl. No.: **13/344,312**

(22) Filed: **Jan. 5, 2012**

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Related U.S. Application Data

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H01L 27/146 (2006.01)
G02B 3/00 (2006.01)

(52) **U.S. Cl.**
CPC ***H01L 27/14627*** (2013.01); ***G02B 3/0018*** (2013.01); ***H01L 27/1464*** (2013.01); ***H01L 27/14685*** (2013.01)

(58) **Field of Classification Search**
None
See application file for complete search history.

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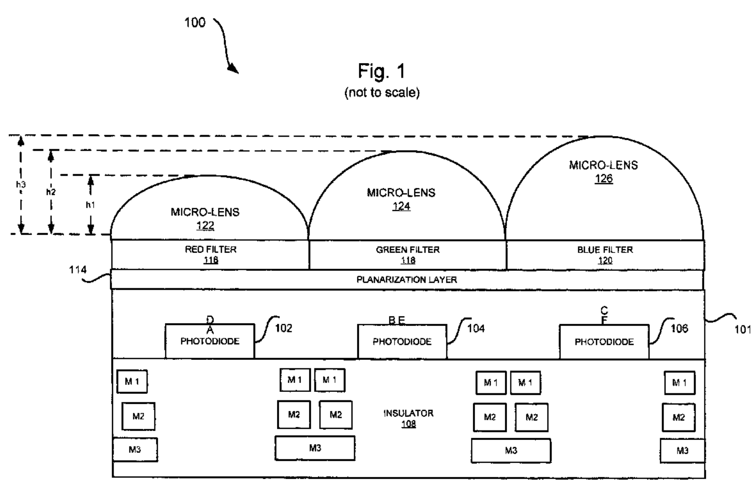
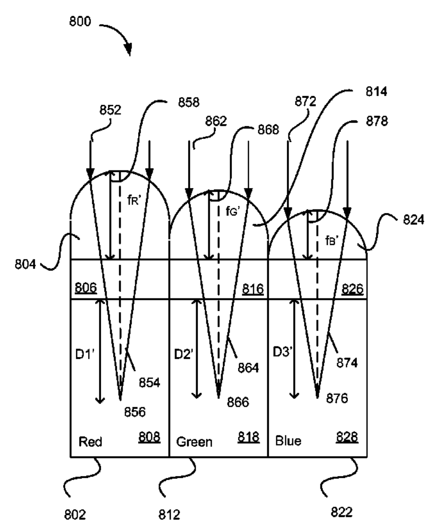
(57) **ABSTRACT**

An example image sensor includes first, second, and third micro-lenses. The first micro-lens is in a first color pixel and has a first curvature and a first height. The second micro-lens is in a second color pixel and has a second curvature and a second height. The third micro-lens is in a third color pixel and has a third curvature and a third height. The first curvature is the same as both the second curvature and the third curvature and the first height is greater than the second height and the second height is greater than the third height, such that light absorption depths for the first, second, and third color pixels are the same.

9 Claims, 9 Drawing Sheets





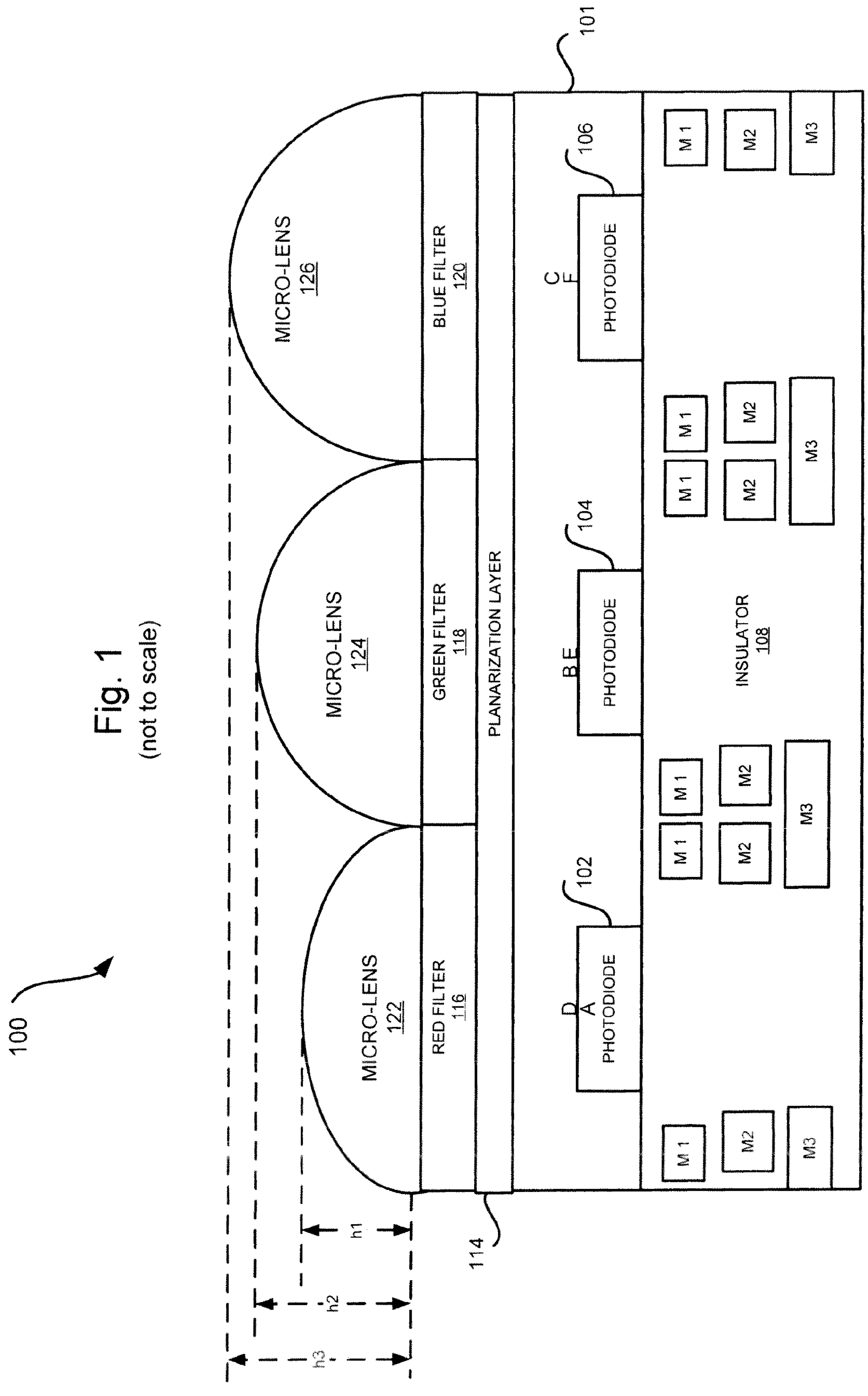


Fig. 1
(not to scale)
100
101
MICRO-LENS
126
MICRO-LENS
124
MICRO-LENS
122
BLUE FILTER
120
GREEN FILTER
118
RED FILTER
116
PLANARIZATION LAYER
114
106
104
102
C
F
B E
D
A
PHOTODIODE
PHOTODIODE
PHOTODIODE
INSULATOR
108
M 1
M2
M3
h1
h2
h3

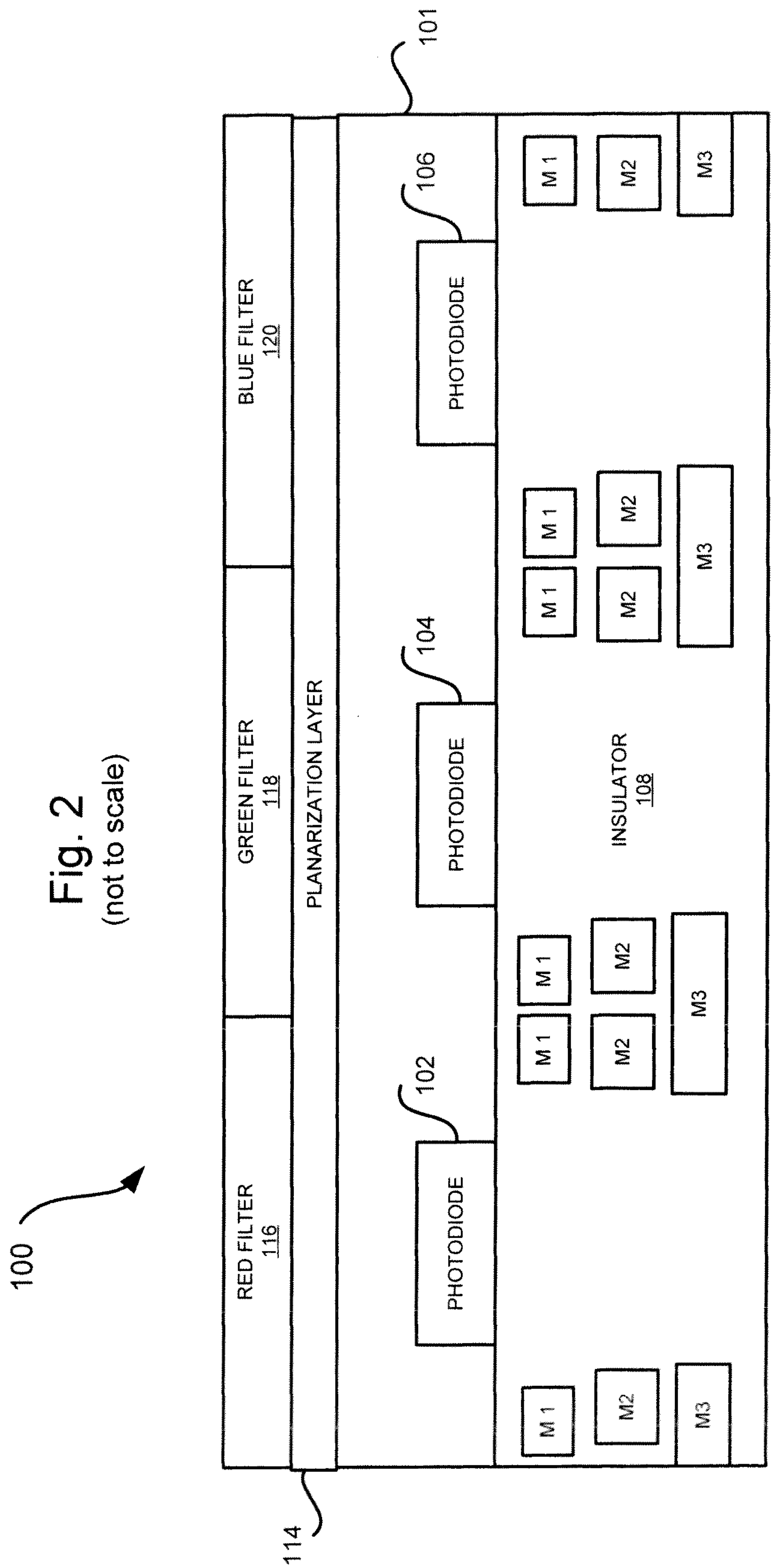


Fig. 2
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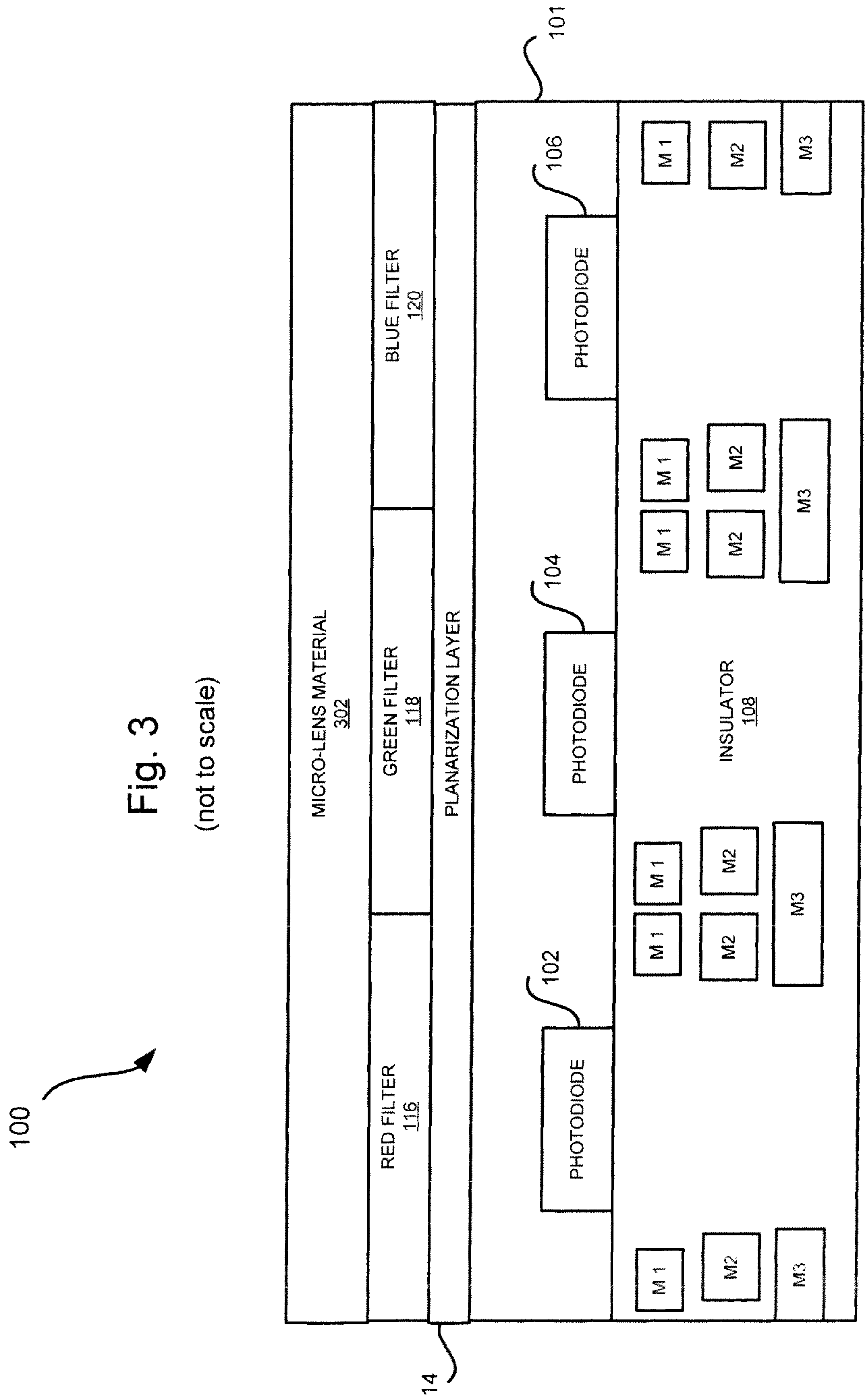

Fig. 3
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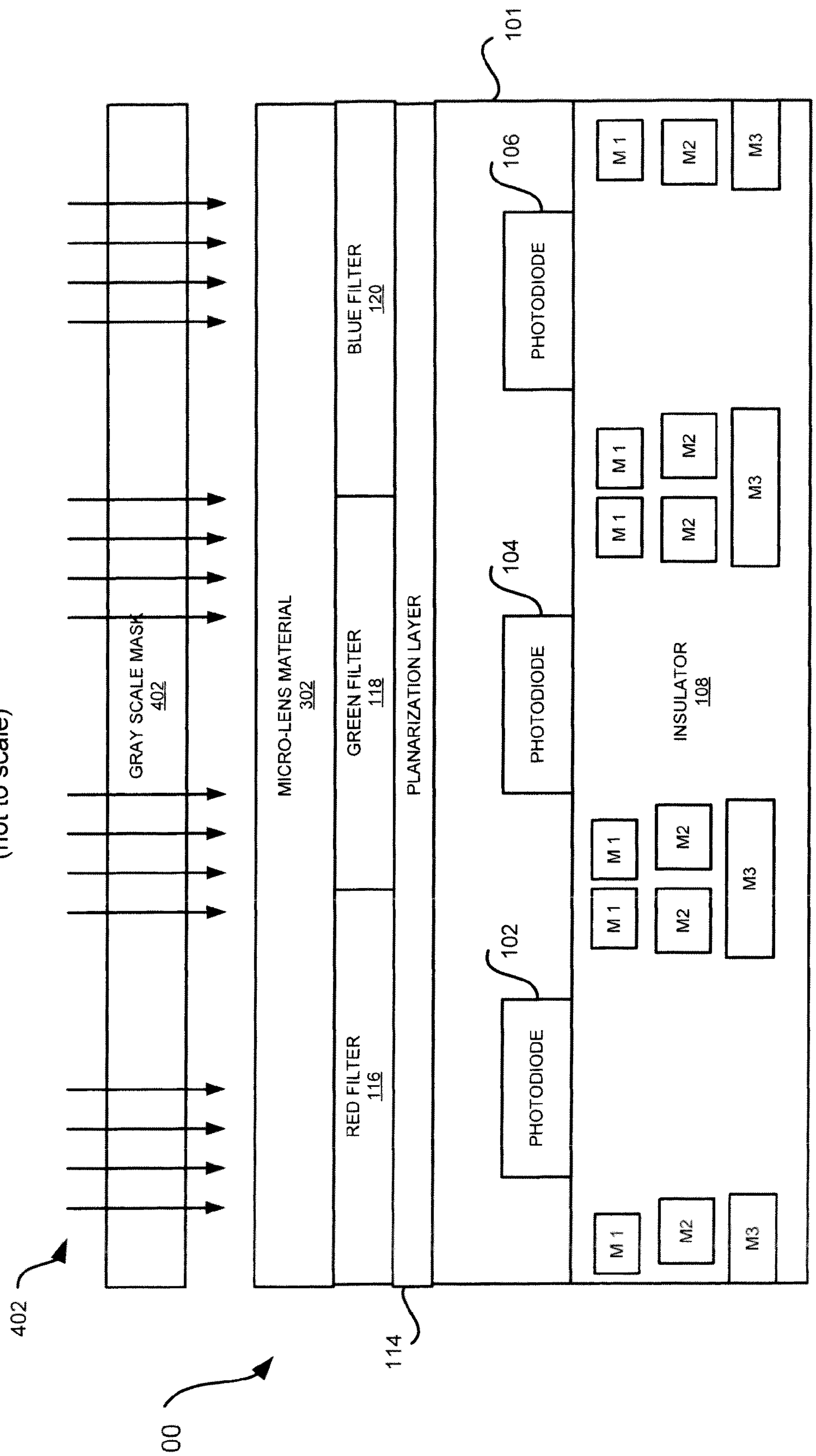

Fig. 4
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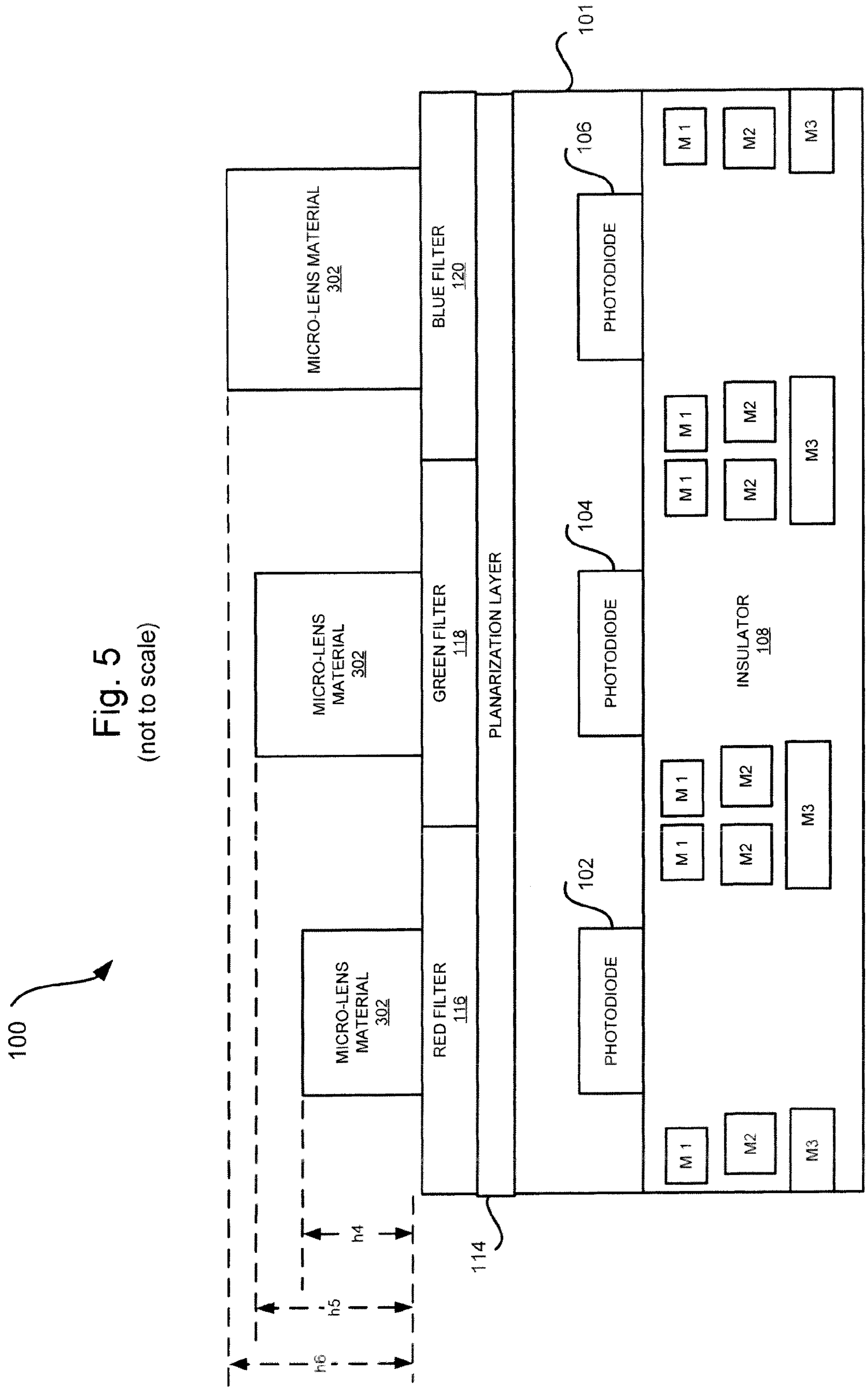

Fig. 5
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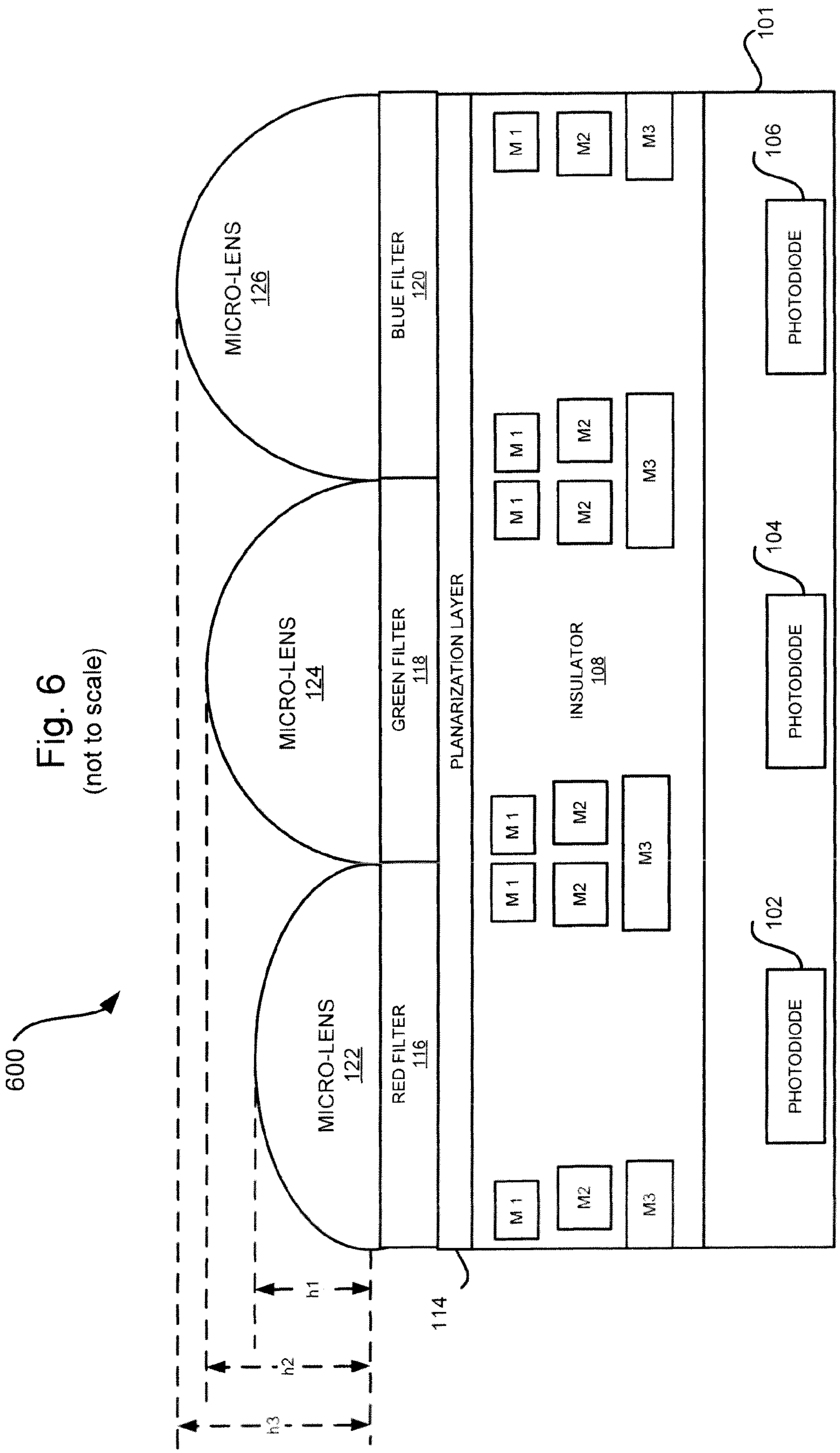
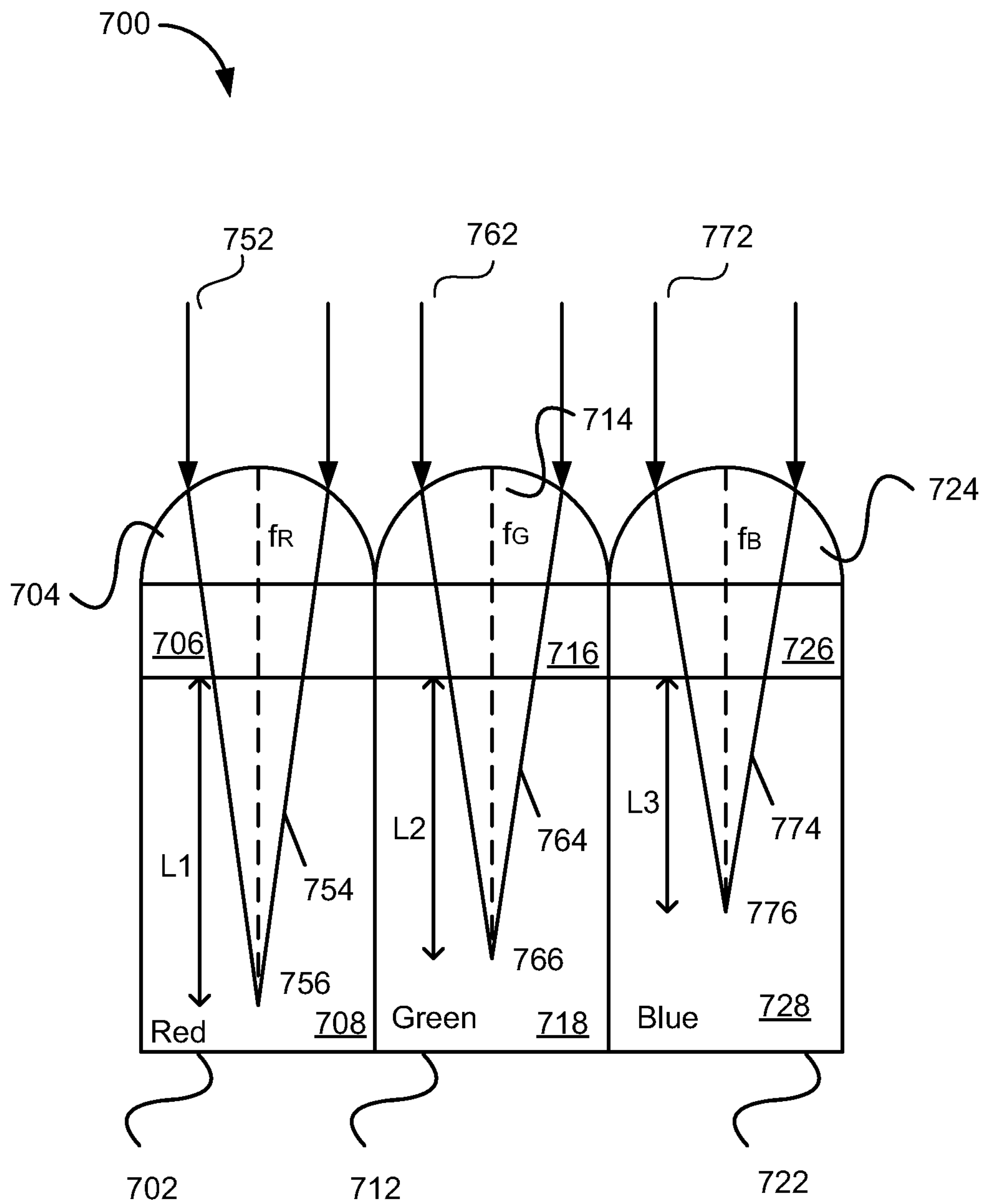


Fig. 6
(not to scale)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772
714
724
704
fR
fG
fB
706
716
726
L1
L2
L3
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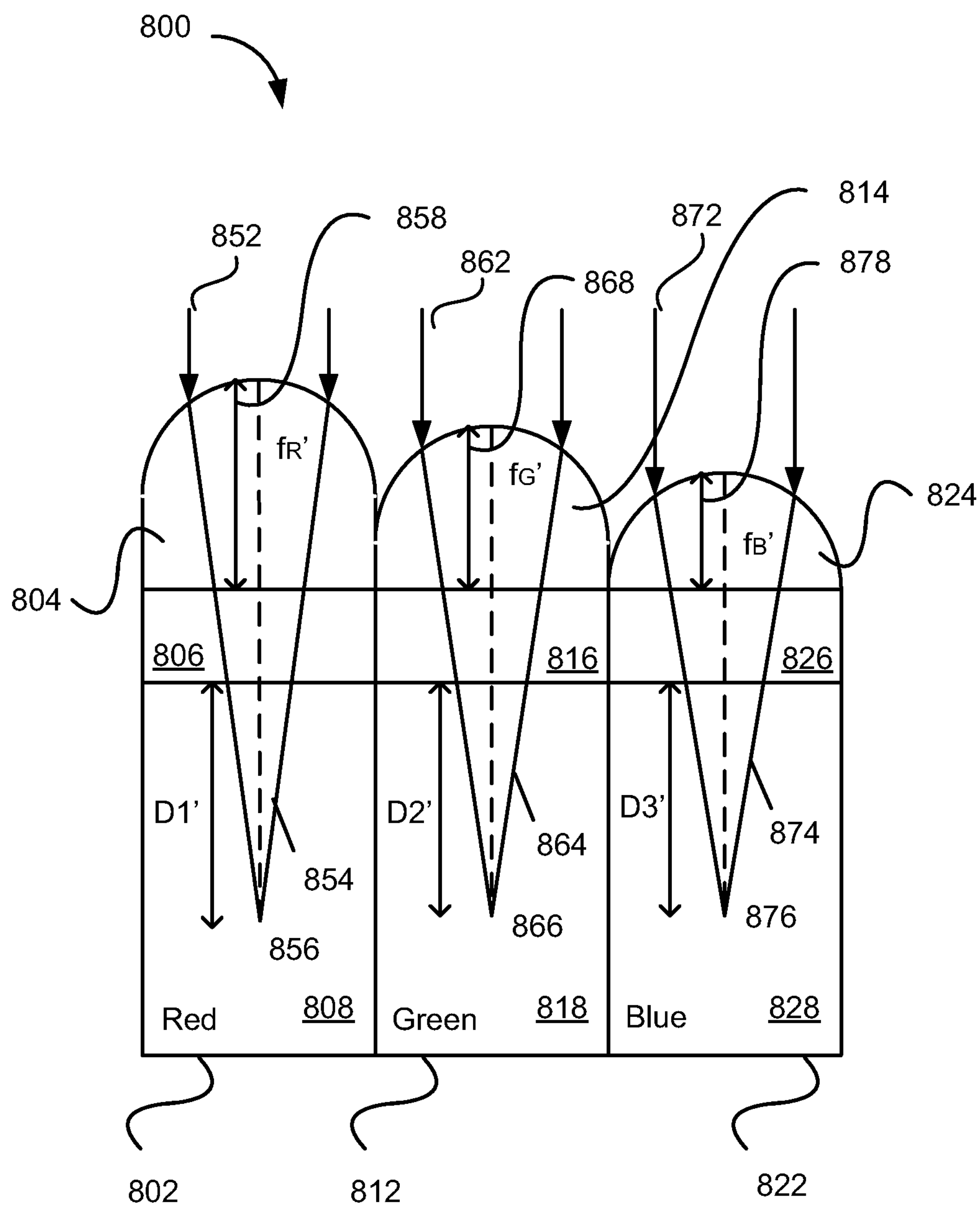
764
774
776
766
756
Red
708
Green
718
Blue
728
702
712
722

Fig. 7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D1'
D2'
D3'
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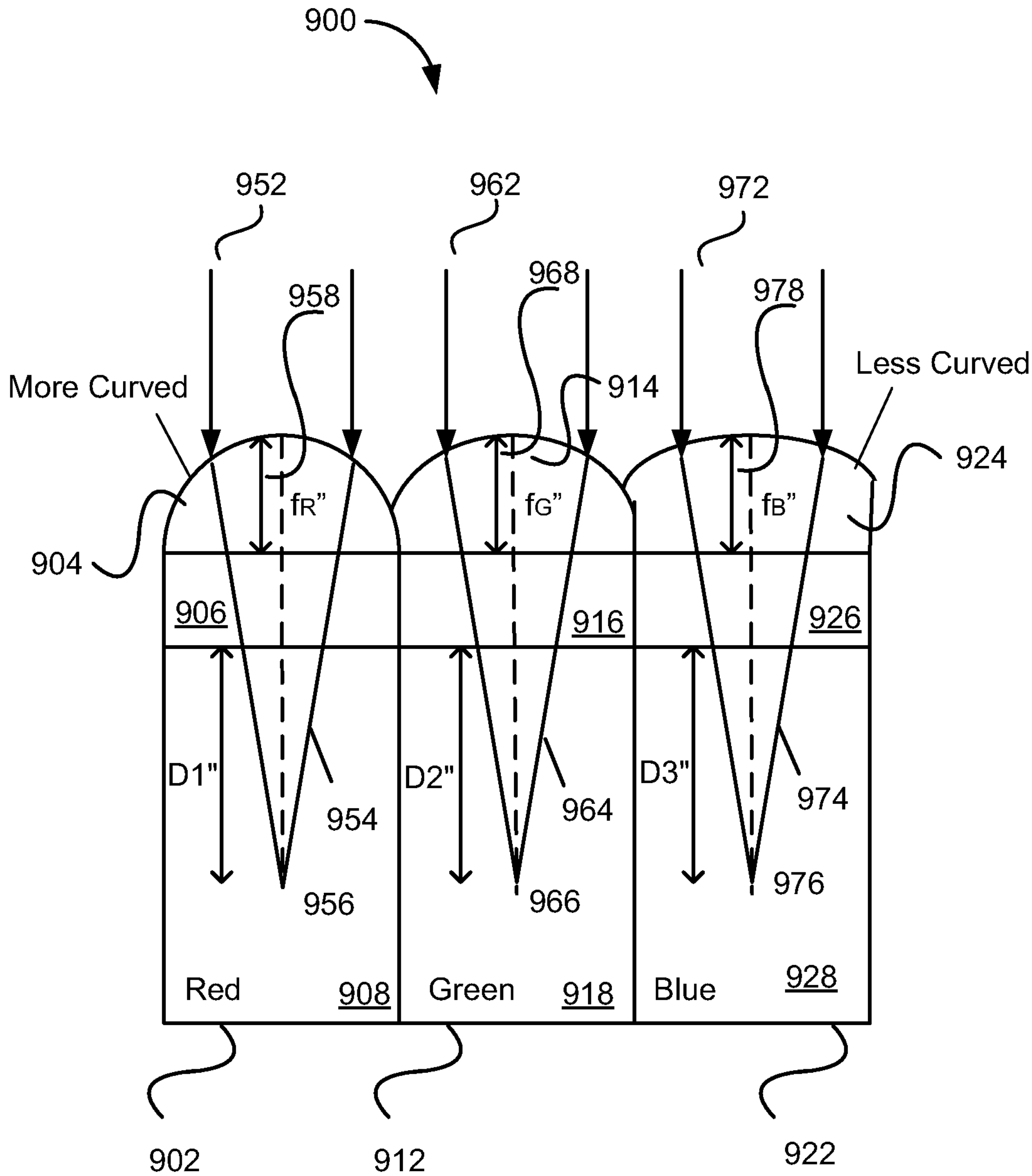
Blue
828
802
812
822

Fig. 8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978
914
More Curved
Less Curved
924
904
fR"
fG"
fB"
906
916
926
D1"
D2"
D3"
954
964
974
956
966
976
Red
908
Green
918
Blue
928
902
912
922

Fig. 9

IMAGE SENSOR WITH COLOR PIXELS HAVING UNIFORM LIGHT ABSORPTION DEPTHS

REFERENCE TO PRIOR APPLICATION

This application is a continuation-in-part of U.S. application Ser. No. 12/029,400, filed Feb. 11, 2008, titled IMAGE SENSOR WITH MICRO-LENSES OF VARYING FOCAL LENGTHS.

BACKGROUND

1. Field

Embodiments of the present invention relate to image sensors and, in particular, to micro-lenses for image sensors.

2. Discussion of Related Art

In general, conventional image sensors perform well to generate images. A typical image sensor may be fabricated from a complementary metal oxide semiconductor (CMOS) technology. Charge coupled device (CCD) technology is also suitable.

A typical image sensor includes an array of picture elements or pixels. An individual pixel is made up of a photodetector, one or more light filters, and a micro-lens. The typical image sensor operates as follows. Light such as visible light, which is made up of several different colors of light, is incident on the micro-lens. The micro-lens focuses the light to the photodetector through the light filter. The photodetector converts the light into an electrical signal proportional to the intensity of the light detected. Conventional image sensors suffer from some limitations, however. For example, the response of one pixel to a specific color may be better or worse than the pixel's response to another color.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings, like reference numbers generally indicate identical, functionally similar, and/or structurally equivalent elements. The drawing in which an element first appears is indicated by the leftmost digit(s) in the reference number, in which:

FIG. **1** is a side view of an image sensor that has micro-lenses of varying heights, shapes, curvatures, and/or focal lengths according to an embodiment of the present invention;

FIG. **2** is a side view of the image sensor in FIG. **1** undergoing a fabrication process according to an embodiment of the present invention;

FIG. **3** is a side view of the image sensor in FIG. **1** undergoing a fabrication process according to an embodiment of the present invention;

FIG. **4** is a side view of the image sensor in FIG. **1** undergoing a fabrication process according to an embodiment of the present invention;

FIG. **5** is a side view of the image sensor in FIG. **1** undergoing a fabrication process according to an embodiment of the present invention; and

FIG. **6** is a side view of an image sensor that has micro-lenses of varying heights, shapes, curvatures, and/or focal lengths according to an alternative embodiment of the present invention;

FIG. **7** is a side view of an image sensor with varying light absorption depths;

FIG. **8** is a side view of an image sensor that has micro-lenses of varying heights, in accordance with an embodiment of the present invention;

FIG. **9** is a side view of an image sensor that has micro-lenses of varying curvatures, in accordance with an embodiment of the present invention.

DETAILED DESCRIPTION OF EMBODIMENTS

In the below description, numerous specific details, such as, for example, particular processes, materials, devices, and so forth, are presented to provide a thorough understanding of embodiments of the invention. One skilled in the relevant art will recognize, however, that the embodiments of the present invention may be practiced without one or more of the specific details, or with other methods, components, etc. In other instances, structures or operations are not shown or described in detail to avoid obscuring the understanding of this description.

Reference throughout this specification to "one embodiment" or "an embodiment" means that a particular feature, structure, process, block, or characteristic described in connection with an embodiment is included in at least one embodiment of the present invention. Thus, the appearance of the phrases "in one embodiment" or "in an embodiment" in various places throughout this specification does not necessarily mean that the phrases all refer to the same embodiment. The particular features, structures, or characteristics may be combined in any suitable manner in one or more embodiments.

According to some embodiments of the present invention, a complimentary metal oxide semiconductor (CMOS) image sensor may have an array of pixels. At least two pixels may have a micro-lenses disposed therein. The heights of the micro-lenses may be different from each other. Alternatively, the shapes of the micro-lenses may be different from each other. Alternatively still, the focal lengths of the micro-lenses may be different from each other. One advantage of having an image sensor that has micro-lenses with varying shapes, heights, curvatures, and/or focal lengths according to embodiments of the present invention is that the responsiveness of one pixel to a particular color (e.g., black white, grays, red, blue green, etc.) may be improved while the responsiveness of the other pixel to another color also may be improved. That is, pixels can be tailored to respond to particular colors. Embodiments of the present invention use a gray scale mask to tailor the pixels to the particular color. Other features and advantages of the present invention will be apparent from the accompanying drawings and from the detailed description that follows.

FIG. **1** is a side view of an image sensor **100** that has micro-lenses of varying heights, shapes, and/or focal lengths according to an embodiment of the present invention. Generally, the image sensor **100** includes several photosensitive elements arranged in an array of two dimensional rows and columns in a substrate **101**.

In the illustrated embodiment, there are three photosensitive elements, which are shown as photodiodes **102**, **104**, and **106**. Of course, the array can include upwards of thousands of rows and/or columns, or more. Similarly, the array may have an arrangement other than columns and rows.

On one side of the substrate **101**, several metal conductors M**1**, M**2**, and M**3** are disposed in an insulator **108**. A planarization/passivation layer **114** is disposed on another side of the substrate **101**. Several filters shown as a red filter **116**, a green filter **118**, and a blue filter **120** are disposed on the planarization/passivation layer **114**. A micro-lens **122** is disposed on the red filter **116**, a micro-lens **124** is disposed on the green filter **118**, and a micro-lens **126** is disposed on the blue filter **120**.

For some embodiments, the refraction of the micro-lenses **122**, **124**, and/or **126** varies with the wavelength of incident light. The wavelength of red light is greater than the wavelength of green light, which is greater than the wavelength of blue light. Thus, when white light passes through lenses, blue light is refracted more than green light and red light is refracted more than green light. If the micro-lenses **122**, **124**, and/or **126** were the same shape, height, and had the same focal lengths, red light may be incident on the photodiode **102** at a point A, green light may be incident on the photodiode **104** at a point B, and blue light may be incident on the photodiode **106** at a point C. These points are not necessarily optimal for detecting light.

According to embodiments of the present invention, the micro-lenses **122**, **124**, and/or **126** have different shapes, heights, and/or focal lengths. As a result, red light may be incident on the photodiode **102** at a point D, green light may be incident on the photodiode **104** at a point E, and blue light may be incident on the photodiode **106** at a point F. These points may be better for detecting the light.

For some embodiments, the focal length f of the micro-lens **122** is smaller than the focal length of the micro-lens **124**, which is smaller than the focal length of the micro-lens **126**. Among other things, the colors or peak wavelengths of the filters **116**, **118**, and **120**, the thicknesses of the micro-lenses **122**, **124**, and **126**, the radius of curvature for the surface of the micro-lens where light is incident on the micro-lenses **122**, **124**, and **126**, etc., may determine the focal length of a particular micro-lenses **122**, **124**, and **126**. For some embodiments, the thickness of a micro-lens may be in the range of approximately 0.3 to 3.0 micrometers.

In the illustrated embodiment, the micro-lens **122** has a height h**1**, the micro-lens **124** has a height h**2**, and the micro-lens **126** has a height h**3**. Note that h**3** is greater than h**2**, which is greater than h**1**. During fabrication, the heights or thicknesses of the micro-lenses **122**, **124**, and **126** are determined based on the desired focal lengths for the micro-lenses **122**, **124**, and **126**. That is, the different heights result in different focal lengths for the micro-lenses **122**, **124**, and **126**. In the illustrated embodiment, the micro-lenses **122**, **124**, and **126** also have different shapes, which are determined based on, among other things, the desired focal lengths.

Because the micro-lenses **122**, **124**, and **126** have different shapes, heights, and/or focal lengths, more red light may fall on the pixel made up of the photodiode **102**, the red filter **116**, and the micro-lens **122**. Similarly, more green light may fall on the pixel made up of the photodiode **104**, the green filter **118**, and the micro-lens **124**. Likewise, more blue light may fall on the pixel made up of the photodiode **106**, the blue filter **120**, and the micro-lens **126**. That is, each pixel may be tailored to respond its associated color or peak wavelength.

For some embodiments, the substrate **101** may be a semiconductor substrate. For some embodiments, the substrate **101** is a doped silicon substrate.

For some embodiments, the photosensitive elements **102**, **104**, and **106** may be any suitable device that converts light into an electric signal. The photosensitive element may be a photodiode as shown or other solid state device. Other photosensitive elements also may be utilized as well.

For some embodiments, the dielectric material **108** may be any suitable insulator such as an oxide. For some embodiments, the dielectric material may be a silicon oxide.

For some embodiments, the M**1**, M**2**, and M**3** metal conductors may be copper, aluminum, an aluminum-copper mixture, or other metal suitable for carrying a signal. The dielectric material **108** may insulate the M**1**, M**2**, and M**3** metal conductors from each other and the substrate **101**.

For some embodiments, the planarization/passivation layer **114** may protect or planarize the substrate **101**.

In the illustrated embodiment, the filter **116** is a red filter that substantially allows red light to pass but blocks substantially all other light in the visible spectrum, the filter **118** is a green filter that substantially allows green light to pass but blocks substantially all other light in the visible spectrum, and the filter **120** is a blue filter that substantially allows blue light to pass but blocks substantially all other light in the visible spectrum. Although the filters are shown as a red filter **116**, a green filter **118**, and a blue filter **120**, they need not be these colors. The filters **116**, **118**, and/or **120** may be cyan, magenta, and/or yellow. Other colors are suitable as well. The filters **116**, **118**, and **120** may be made from any suitable material. One suitable material for the filters **116**, **118**, and/or **120** is an acrylic. Polymethylmethacrylate (PMMA) or polyglycidylmethacrylate (PGMA) that has been pigmented or dyed is suitable for embodiments in which the filters are color filter. Other photoresist-type materials that can be dyed or pigmented may also be used.

Although shown as color filters, the filters **116**, **118**, and/or **120** need not be. For some embodiments, the filters **116**, **118**, and/or **120** may be filters for black and white photography.

Fabrication of the image sensor **100** according to at least one embodiment will now be described with reference to FIG. **2** through FIG. **5**. The embodiment shown in FIG. **2** shows a first step in the fabrication process. For example, FIG. **2** is a side view of the image sensor **100** without the micro-lenses **122**, **124**, and **126** according to an embodiment of the present invention.

The illustrated embodiment shows/illustrates the photodiodes **102**, **104**, and **106**; the metal conductors M**1**, M**2**, and M**3** are disposed in the insulator **108**; the planarization/passivation layer **114** is disposed on the insulator **108**; and the red filter **116**, green filter **118**, and blue filter **120** are disposed on the planarization/passivation layer **114**. Techniques for fabricating the image sensor **100** depicted in FIG. **2** are known and include deposition, etching, masking, implantation, growing, photolithography, etc.

The embodiment shown in FIG. **3** shows a next step in the fabrication process. For example, FIG. **3** is a side view of the image sensor **100** with micro-lens material **302** disposed on the filters **116**, **118**, and **120**. For some embodiments, the micro-lens material **302** may be disposed using spin-on techniques, blanket deposition techniques, or other methods suitable for disposing the micro-lens material **302** in a substantially planar manner.

The micro-lenses material **302** may be any suitable material. One suitable material is an acrylic. Polymethylmethacrylate (PMMA) or polyglycidylmethacrylate (PGMA) also may be used. Other photoresist-type materials may also be used.

The embodiment shown in FIG. **4** shows a next step in the fabrication process. For example, FIG. **4** is a side view of the image sensor **100** with micro-lens material **302** being exposed to a source **402** through a gray scale mask **404** according to an embodiment of the present invention. The source **402** and the gray scale mask **404** are used to pattern the micro-lens material **302** into blocks of micro-lens material in a single exposure.

In embodiments in which the source **402** is ultraviolet light and the micro-lens material **302** is a positive photoresist, the portion of the micro-lens material **302** that is exposed to source **402** becomes soluble to the micro-lens material **302** developer and the portion of the micro-lens material **302** that is unexposed remains insoluble to the micro-lens material **302** developer. In embodiments in which the source **402** is ultraviolet light and the micro-lens material **302** is a negative photoresist, the portion of the micro-lens material **302** that is exposed to the source **402** becomes relatively insoluble to the micro-lens material **302** developer. The unexposed portion of the micro-lens material **302** is dissolved by the micro-lens material **302** developer.

For some embodiments, using the gray scale mask **404** allows the thickness of the micro-lens material **302** that remains after exposure to the source **402** and developing to vary due to the varying transmissiveness of the gray scale mask **404**. The thickness of the remaining micro-lens material **302** at a given location may depend on the transmissiveness of the gray scale mask **404** at that location.

The embodiment shown in FIG. **5** shows a first step in the fabrication process. For example, FIG. **5** is a side view of the image sensor **100** following exposure and developing of the micro-lens material **302** using the source **402** and the gray scale mask **404** according to an embodiment of the present invention. In the illustrated embodiment, the micro-lens material **302** over the red filter **116** has a height h**4**, the micro-lens material **302** over the green filter **118** has a height h**5**, and the micro-lens material **302** over the blue filter **120** has a height h**6**. Note that h**6** is greater than h**5**, which is greater than h**4**.

According to embodiments of the present invention, once the micro-lens material **302** is patterned and developed, the remaining micro-lens material **302** may be heated. The micro-lens material **302** may reflow, forming a curvature on the micro-lens material **302**. The curvature of the micro-lens material **302** may be different for the micro-lens material **302** over the red filter **116**, the micro-lens material **302** over the green filter **118**, and the micro-lens material **302** over the blue filter **120**. This is because the micro-lens material **302** over the red filter **116** has the height h**4**, the micro-lens material **302** over the green filter **118** has the height h**5**, and the micro-lens material **302** over the blue filter **120** has the height h**6**. After reflow, the result may be the micro-lens **122** having the height h**1**, the micro-lens **124** having the height h**2**, and the micro-lens **126** having the height **128**, as illustrated in FIG. **1**.

Alternatively, the curvature of the micro-lens material **302** may be the same for the micro-lens material **302** over the red filter **116**, the micro-lens material **302** over the green filter **118**, and the micro-lens material **302** over the blue filter **120**, but their heights may be different after reflow processing. The different heights also may be tailored to the particular color to be processed by the photosensitive element.

In the embodiment illustrated in FIG. **1**, the micro-lenses **122**, **124**, and **126**, the filters **116**, **118**, and **120**, and the planarization/passivation layer **114**, are on one side of the substrate **101** and the M**1**, M**2**, and M**3** metal conductors disposed in the insulator **108** are on another side of the substrate **101**. This embodiment may be referred to as a back side illumination (BSI) embodiment. In back side illumination, light does not go through the metal conductors M**1**, M**2**, and M**3** before reaching the photodiodes **102**, **104**, and **106**. That is, light paths to the points D, E, and F the photodiodes **102**, **104**, and **106**, respectively, do not include the metal layers.

One advantage of back side illuminated image sensors is that as the image sensors become more complex more metal layers may be added without increasing the length of the optical path to the photodetectors. Additionally, the metal conductors in the metal layers may be spaced closer together without substantially affecting the optical path to the photodetectors.

FIG. **6** is a side view of an image sensor **600** that has micro-lenses of varying heights, shapes, curvatures, and/or focal points according to an alternative embodiment of the present invention in which the image sensor **600** is front side illuminated (FSI). In the embodiment illustrated in FIG. **1**, the micro-lenses **122**, **124**, and **126**, the filters **116**, **118**, and **120**, and the planarization/passivation layer **114**, are on one side of the substrate **101** and the M**1**, M**2**, and M**3** metal conductors disposed in the insulator **108** are on another side of the substrate **101**. Although illustrated with the same heights h**1**, h**2**, and h**3**, the heights of the microlenses **122**, **124**, and **126** may be different.

FIG. **7** illustrates an image sensor **700** having microlenses of the same height and curvature for each of the color pixels (e.g., **702**, **712**, and **722**). For example, red pixel **702** includes a microlens **704**, a red color filter **706**, and a light sensitive element (e.g., photodiode) **708**. Green pixel **712** includes a microlens **714**, a green color filter **716**, and a light sensitive element **718**. Blue pixel **722** includes a microlens **724**, a blue color filter **726**, and a light sensitive element **728**. Microlenses **704**, **714**, and **724** are identical in that they have the same height, curvature, and may be made from the same material (i.e., same index of refraction). However, image sensor **700** may have some deficiencies. For example, visible incoming light **752** is focused by microlens **704** and filtered by red color filter **706**. Filtered light **754** has a center wavelength corresponding to red color. Light **754** is focused in light sensitive element **708**. Light **754** travels a distance L**1** in light sensitive element **708** to reach its focus **756**. If light **754** is not completely absorbed in distance L**1**, the remaining part of light **754** diverges from focus **756** and may escape from red pixel **702** to neighboring pixels of different colors.

To improve light absorption or quantum efficiency, microlens **704** may be designed to have focus **756** at a depth that light **754** is completely absorbed in distance L**1**. The focal length of a lens depends on the wavelength of light. A longer wavelength has a longer focal length. Consequently, $f_R>f_G>f_B$, where f_R is the red focal length, f_G is the green focal length, and f_B is the blue focal length. Thus, for microlenses **704**, **714**, and **724**, red focus **756** is deeper than green focus **766**, and green focus **766** is deeper than blue focus **776**. Consequently, green light **764** and blue light **774** may not be absorbed completely at their respective focal points although red light **754** is absorbed completely, because distance L**3** is less than distance L**2**, and distance L**2** is less than distance L**1**. This may cause low quantum efficiency, crosstalk, and color imbalance. Note that a substrate and/or a planarization/passivation layer may be disposed between color filters and light sensitive elements (e.g., photodiodes) as illustrated in FIG. **1**.

FIG. **8** shows an embodiment **800**, in which all microlenses have the same curvature. Thus, the focal lengths of microlenses are approximately the same as those in FIG. **7**. In other words, $f_R'\approx f_R$, $f_G'\approx f_G$, and $f_B'\approx f_B$, where f_R', f_G', and f_B' are new focal lengths according to the embodiment illustrated in FIG. **8**, and f_R, f_G, and f_B are focal lengths illustrated in FIG. **7**. Microlenses **804**, **814**, and **824** have a uniform curvature, where the "curvature of a lens" refers to the amount by which the lens deviates from being flat. However, microlenses **804** and **814** are elevated to adjust the positions of focus relative to the light sensitive elements. For example, microlens **804** of red pixel **802** has a height **858** that is greater than the height **868** of microlens **814** of green pixel **812**, and height **868** is greater than the height **878** of microlens **824** of blue pixel **822**. In other words, height **858**>height **868**>height **878**. In one embodiment, heights **858**, **868**, and **878** refer to the distance from their color filter to a uppermost point of their respective microlenses. Microlenses **804**, **814**, and **824** may be fabricated using a gray scale mask as described in previous paragraphs.

Although all microlenses **804**, **814**, and **824** have approximately unchanged focal lengths relative to FIG. **7**, red focus **856** from incoming light **852**, green focus **866** from incoming light **862**, and blue focus **876** from incoming light **872** have a uniform depth because microlenses **804** and **814** have been elevated accordingly. In other words, light paths **854**, **864**, and **874** in light sensitive elements **808**, **818**, and **828** travel the same distance, D**1**'=D**2**'=D**3**' to reach focus **856**, **866**, and **876**, respectively. In one embodiment, depths D**1**', D**2**', and D**3**' are the total light absorption depths for their respective pixels, where substantially all of the received light has been absorbed by their respective light sensitive elements in the distances D**1**', D**2**', and D**3**'. In some instances, all foci may be at the bottom of light sensitive elements. Note that a substrate and/or a planarization/passivation layer may be disposed between color filters and light sensitive elements (e.g., photodiodes) as illustrated in FIG. **1**.

Alternatively, the microlenses may be fabricated to have different shapes or curvatures, so the microlenses will have different focal lengths. A layer of photoresist type microlens material is exposed to a light source through a gray scale mask. Only a single exposure is required. Parts of microlens layer that are more exposed to light corresponding to the parts of the gray scale mask having higher transmissiveness will have larger thickness or less thickness depending on whether the layer is a negative or positive photoresist. Similarly, parts of microlens layer that are less exposed to light corresponding to the parts of the gray scale mask having lower transmiveness will have less thickness or larger thickness depending on whether the layer is a negative or positive photoresist. A positive photoresist is a type of photoresist in which the portion of the photoresist that is exposed to light becomes soluble to the photoresist developer. The portion of the photoresist that is unexposed remains insoluble to the photoresist developer. A negative photoresist is a type of photoresist in which the portion of the photoresist that is exposed to light becomes insoluble to the photoresist developer. The unexposed portion of the photoresist is dissolved by the photoresist developer. Thus, a microlens having a certain curvature or shape can be manufactured by developing the exposed positive photoresist or negative photoresist. The curvature or shape of microlens is according to a pattern of varying transmissiveness of the gray scale mask.

FIG. **9** shows an embodiment **900**, in which microlenses have different curvatures and approximately the same heights (e.g., height **958**=height **868**=height **978**). Accordingly, $f_R'' \neq f_R$, $f_G'' \neq f_G$, and $f_B'' \neq f_B$, where f_R'', f_G'', and f_B'' are new focal lengths shown in FIG. **9**, and f_R, f_G, and f_B are focal lengths illustrated in FIG. **7**. For example, microlens **904** of red pixel **902** is more curved than microlens **914** of green pixel **912**, and microlens **914** is more curved than microlens **924** of blue pixel **922**. Thus, light paths **954**, **964**, and **974** in light sensitive elements **908**, **918**, and **928** travel a uniform distance, D**1**"=D**2**"=D**3**" to reach focus **956**, **966**, and **976**, respectively. In one embodiment, depths D**1**", D**2**", and D**3**" are the total light absorption depths for their respective pixels, where substantially all of the received light has been absorbed by their respective light sensitive elements in the distances D**1**", D**2**", and D**3**". Microlenses **904**, **914**, and **924** may be fabricated using a gray scale mask as described in previous paragraphs. In some instances, all focus may be at the bottom of light sensitive elements. Note that a substrate and/or a planarization/passivation layer may be disposed between color filters and light sensitive elements (e.g., photodiodes) as illustrated in FIG. **1**.

In some instances, a light sensitive element has a spectral response. For example, light sensitive element may be Si-epi.

In Si-epi, blue light is absorbed faster than green light, and green light is absorbed faster than red light. In other words, at the same intensity, red light will be completely absorbed in a distance D**1**, green light will be completely absorbed in a distance D**2**, and blue light will be completely absorbed in a distance D**3**, wherein D**1** is larger than D**2**, and D**2** is larger than D**3** (D**1**>D**2**>D**3**). Accordingly, in a embodiment of FIG. **8** where light sensitive elements are Si-epi, D**1**'>D**2**'>D**3**' may be preferred, where D**1**", D**2**", and D**3**" are distances of red, green and blue light paths in light sensitive elements, respectively. Therefore, the height **858** of red microlens **804** may be less than the height **868** of green microlens **814**, and the height **868** of green microlens **814** may be less than the height **878** of blue microlens **824**. Also, in contrast to FIG. **9**, a red microlens may be less curved than the green microlens, and the green microlens less curved than the blue microlens.

Embodiments of the present invention may be implemented using hardware, software, or a combination thereof. In implementations using software, the software or machine-readable data may be stored on a machine-accessible medium. The machine-readable data may be used to cause a machine, such as, for example, a processor (not shown) to perform the method and processes herein. A machine-readable medium includes any mechanism that may be adapted to store and/or transmit information in a form accessible by a machine (e.g., a computer, network device, personal digital assistant, manufacturing tool, any device with a set of one or more processors, etc.). For example, a machine-readable medium includes recordable and non-recordable media (e.g., read only (ROM), random access (RAM), magnetic disk storage media, optical storage media, flash devices, etc.).

The terms used in the following claims should not be construed to limit embodiments of the invention to the specific embodiments disclosed in the specification and the claims. Rather, the scope of embodiments of the invention is to be determined entirely by the following claims, which are to be construed in accordance with established doctrines of claim interpretation.

What is claimed is:

1. An image sensor, comprising:

a first micro-lens positioned on a first color filter that is optically coupled to a first light-sensitive element, the first micro-lens having a first curvature and a first height;

a second micro-lens positioned on a second color filter that is optically coupled to a second light-sensitive element, the second micro-lens having a second curvature and a second height; and

a third micro-lens positioned on a third color filter that is optically coupled to a third light-sensitive element, the third micro-lens having a third curvature and a third height;

wherein the first micro-lens, the second micro-lens, and the third micro-lens are made of a single layer of the same material,

wherein the first curvature is the same as both the second curvature and the third curvature, wherein the first height is greater than the second height and the second height is greater than the third height, such that light absorption depths in the first, second, and third light-sensitive elements are the same, and wherein the first, second, and third color filters have the same thickness, and

wherein the first color filter is disposed on the first light-sensitive element, the second color filter is disposed on the second light-sensitive element, and the third color filter is disposed on the third light-sensitive element.

2. The image sensor of claim 1, wherein the first color filter is red, the second color filter is green, and the third color filter is blue.

3. The image sensor of claim 1, wherein the each of the first, second, and third micro-lenses comprise photoresist, and wherein

the first height corresponds to a first transmissiveness at a first location of a gray scale mask;

the second height corresponds to a second transmissiveness at a second location of the gray scale mask; and

the third height corresponds to a third transmissiveness at a third location of the gray scale mask, wherein the first transmissiveness, the second transmissiveness, and the third transmissiveness are different from each other.

4. The image sensor of claim 3, wherein the first, the second, and the third micro-lenses are patterned by the gray scale mask in a single exposure.

5. A backside-illuminated image sensor comprising:

a substrate having a front side and a back side, the front side having formed therein a first light-sensitive element, a second light-sensitive element, and a third light-sensitive element;

first, second, and third color filters formed on the back side of the substrate so that the first color filter is optically coupled to the first light-sensitive element, the second color filter is optically coupled to the second light-sensitive element, and the third color filter is optically coupled to the third light-sensitive element; and

first, second, and third micro-lenses positioned on the first, second, and third color filters, wherein the first micro-lens has a first curvature and a first height, the second micro-lens has a second curvature and a second height, and the third micro-lens has a third curvature and a third height and wherein the first micro-lens, the second micro-lens, and the third micro-lens are made of a single layer of the same material;

wherein the first curvature is the same as both the second curvature and the third curvature, wherein the first, second, and third color filters have the same thickness, and wherein the first height is greater than the second height and the second height is greater than the third height, such that light absorption depths in the first, second, and third light-sensitive element are the same.

6. The image sensor of claim 5, further comprising a planarizing layer formed between the back side of the substrate and the first, second, and third color filters.

7. The image sensor of claim 5 wherein the first color filter is red, the second color filter is green, and the third color filter is blue.

8. The image sensor of claim 5 wherein the first, second, and third micro-lenses are patterned by the gray scale mask in a single exposure.

9. An image sensor comprising:

a first micro-lens positioned on a first color filter that is optically coupled to a first light-sensitive element, the first micro-lens having a first curvature and a first height;

a second micro-lens positioned on a second color filter that is optically coupled to a second light-sensitive element, the second microlens having a second curvature and a second height; and

a third micro-lens positioned on a third color filter that is optically coupled to a third light-sensitive element, the third micro-lens having a third curvature and a third height;

wherein the first micro-lens, the second micro-lens, and the third micro-lens are made of a single layer of the same material;

wherein the first curvature is the same as both the second curvature and the third curvature, wherein the first height is greater than the second height and the second height is greater than the third height, and wherein the first, second, and third color filters have the same thickness;

wherein the first color filter is disposed on the first light-sensitive element, the second color filter is disposed on the second light-sensitive element, and the third color filter is disposed on the third light-sensitive element;

wherein the first, second, and third light sensitive elements each include epitaxial silicon;

wherein the first light sensitive element is configured to receive blue light along a first light path having a first distance within the first light sensitive element, the second light sensitive element is configured to receive green light along a second light path having a second distance within the second light sensitive element, and the third light sensitive element is configured to receive red light along a third light path having a third distance within the third light sensitive element, wherein the third distance is greater than the second distance, and wherein the second distance is greater than the first distance; and

wherein substantially all of the received blue light is completely absorbed in the first distance, substantially all of the received green light is completely absorbed in the second distance, and substantially all of the received red light is completely absorbed in the third distance.

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